The Rise of the Remarkable Type IIn Supernova SN 2009ip

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ABSTRACT

Recent observations by Mauerhan et al. have shown the unprecedented transition of the previously identified luminous blue variable (LBV) and supernova impostor SN 2009ip to a real Type IIn supernova (SN) explosion. We present high-cadence optical imaging of SN 2009ip obtained between 2012 UT Sep. 23.6 and Oct. 9.6, using $0.3-0.4$ meter aperture telescopes from the Coral Towers Observatory in Cairns, Australia. The light curves show well-defined phases, including very rapid brightening early on (0.5 mag in 6 hr observed during the night of Sep. 24), a transition to a much slower rise between Sep. 25 and Sep. 28, and a plateau/peak around Oct. 7. These changes are coincident with the reported spectroscopic changes that, most likely, mark the start of a strong interaction between the fast SN ejecta and a dense circumstellar medium formed during the LBV eruptions observed in recent years. In the 16-day observing period SN 2009ip brightened by 3.7 mag from $I = 17.4$ mag on Sep. 23.6 ($M_I \simeq -14.2$) to $I = 13.7$ mag ($M_I \simeq -17.9$) on Oct. 9.6, radiating $\sim 2\times10^{49}$ erg in the optical wavelength range. Currently, SN 2009ip is more luminous than most Type IIP SNe and comparable to other Type IIn SNe.

Subject headings: circumstellar matter – stars: mass loss – stars: evolution – supernovae: individual (SN 2009ip)

1. Introduction

Establishing an observational mapping between the properties of core-collapse supernovae (ccSNe) explosions (and related luminous outbursts) and local populations of massive

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stars is key for constraining stellar evolution theory (e.g., Langer 2012). Arguably, the best link so far comes from the direct detections of red-supergiants with main-sequence masses $M \simeq 8 - 15$ M$_\odot$ as progenitors of Type IIP supernovae (e.g., Smartt 2009, and references therein), the most common kind of ccSNe. However, direct detections of SN progenitors with higher masses ($M \gtrsim 20$ M$_\odot$) has been elusive (e.g., Kochanek et al. 2008; Smartt 2009).

The detection of a very luminous star ($M_V \sim -10$ mag) identified in pre-explosion images at the location of the Type IIn[1] SN 2005gl provided the first direct evidence for a very massive H-rich star ($\gtrsim 50$ M$_\odot$) that exploded as a luminous ccSN (Gal-Yam et al. 2007; Gal-Yam & Leonard 2009). These observations lend support for the connection made initially by Smith et al. (2007) between one of the most luminous Type IIn SN 2006gy and very massive (~ 100 M$_\odot$) luminous blue variable (LBV) stars like η Carinae. There is now mounting evidence of this connection (e.g., SN 2006jc, Pastorello et al. 2007; SN 2010jl, Smith et al. 2011a; SN 1961V, Kochanek et al. 2011, Smith et al. 2011b), which challenges massive stellar evolution theory in at least two important ways: 1) the most massive stars are not expected to be H-rich at the time when they explode as ccSNe, at least with normal mass-loss prescriptions; and 2) these stars have to loose up to a few solar masses of H-rich material in eruptions just before (months to decades) the core-collapse explosion in order to make them visible as Type IIn SNe. On this last point of timing strong eruptive mass-loss with the core-collapse explosion, there is some very interesting theoretical work, but its still very early days (e.g., Woosley et al. 2007; Arnett & Meakin 2011; Quataert & Shiode 2012; Chevalier 2012).

Luckily, in the last month nature has been kind and has provided the best case to date of a very massive star exploding as a bright core-collapse supernova: SN 2009ip. This transient was discovered on 2009 Aug. 29 by the CHASE survey in the outskirts of the galaxy NGC 7259 (Maza et al. 2009) and was initially given a SN name by the IAU. However, detailed photometric and spectroscopic studies by Smith et al. (2010) and Foley et al. (2011) showed that it never quite reached supernova status. It was actually a supernova impostor (e.g., Humphreys & Davidson 1994, Kochanek et al. 2012; with peak absolute mag. ~ -14, similar to η Carinae's Great Eruption, but significantly shorter timescale), in this case a massive LBV with estimated mass $M \simeq 50-80$ M$_\odot$ (constrained from pre-discovery imaging) that had an eruptive mass-loss event. The Catalina Real-Time Transient Survey (CRTS) discovered another outburst of comparable amplitude during 2010 (Drake et al. 2010) and a third outburst on 2012 July 24 (Drake et al. 2012), the brightest so far. The initial optical spectra obtained by Foley et al. (2012) on Aug. 26 showed narrow emission lines of H and

[1]Dominated by narrow H lines in emission, which indicates a strong interaction between the fast ejecta and a dense circumstellar medium (CSM).

He I, consistent with the spectra obtained in the 2009 outburst. However, an unprecedented change of the spectrum was reported by Smith & Mauerhan (2012a). On Sep. 15 and 16 they had detected very broad emission lines with P-Cygni profiles, consistent with features observed in real Type II SNe; the massive LBV star had probably exploded as a supernova in real time! Another dramatic change in the spectral properties was reported by Smith & Mauerhan (2012b), by Sep. 28 the broad P-Cygni features had mostly disappeared, leaving behind narrow features characteristic of Type IIn SNe. All the details of their discovery and their follow-up observations can be found in Mauerhan et al. (2012b; hereafter M12b). Pastorello et al. (2012; hereafter P12) has also presented detailed follow-up observations of SN 2009ip and propose that the latest outburst might not be the final core-collapse explosion.

In this paper we present high-cadence optical observations of SN 2009ip that clearly resolve the brightening initially reported by Brimacombe (2012). In Section §2 we discuss the observations, data reduction, and extraction of optical light curves using difference imaging photometry. In Section §3 we present an analysis of the different phases of the light curve. In Section §4 we present a discussion of the observed properties. In Section §5 we present the conclusions of this work. We adopt a distance of 20.4 Mpc ($\mu = 31.55$ mag) and Galactic extinction of $A_V = 0.06$ mag towards SN 2009ip (M12b) throughout the paper. All the dates presented in this paper are UT.

2. Observations and Photometry

Imaging of the field of SN 2009ip was obtained by one of us (J. B.) between 2012 Sep. 23.6 and Oct. 9.6 from the Coral Towers Observatory (Cairns, Australia). The data were collected from two different telescopes using different broad-band filters: 33-cm RCOS (with an R filter) and 41-cm RCOS (with an IR luminance filter, which has sharp blue cutoff at 700 nm). The CCD cameras used in both telescopes are identical 3k×2k SBIG STL6K, which give a total field of view of $25' \times 17'$ ($1''$/pix platescale binned 2×2). All the images were obtained using an exposure time of 900 sec. A section of an IR image of SN 2009ip obtained on Sep. 24 is shown in Figure 1.

We used the software MaxIm DL (Version 4.62) to complete the initial data reduction, which consists of bias subtraction, dark subtraction, and flat-fielding. After visually inspecting all images and rejecting frames affected by bad tracking, we kept 85 (R) and 118 (IR) frames for further photometric analysis. We used the image subtraction package ISIS2 (Alard 2000) to extract the fluxes of SN 2009ip in individual frames following the steps described in Hartman et al. (2004). As reference images, we used stacks of $5 - 10$ images with good seeing obtained on Sep. 24-25. We carried out PSF photometry with the DAOPHOT II package (Stetson 1992) to subtract the SN flux and used the resulting SN-subtracted images as the final reference frames.

The SN fluxes obtained with ISIS2 in the R and IR images were calibrated to standard R and I magnitudes, respectively, using data from the AAVSO Photometric All-Sky Survey (APASS[2]). We obtained from APASS calibrated Sloan r' and i' magnitudes of 5 isolated stars in the field of SN 2009ip. We converted these magnitudes in the SDSS photometric system to standard RI (Johnson/Kron-Cousins) photometry using the transformation equations obtained by R. Lupton[3]. In order to estimate the zeropoints, we performed aperture photometry of the 5 local standard stars in the reference images using a $9''$radius aperture with the IRAF task `phot`. The resulting average zeropoints in the RI filters have a standard deviation of 0.02 mag. The final photometry of SN 2009ip calibrated using these zeropoints is presented in Table 1 and the light curves are shown in Figure 1. The errors in each magnitude estimate include poisson errors from ISIS2 as well as the estimated standard error in the photometric zeropoints. Our photometry is in excellent agreement with the results presented in P12, with mean differences during the period of observations of -0.01 ± 0.01 mag in R and -0.02 ± 0.03 mag in I.

3. Analysis

The high cadence and number of observations allow us to clearly resolve the brightening of SN 2009ip, initially reported in Brimacombe (2012) and Prieto et al. (2012). The optical light curves presented in Figure 2 show well-defined phases: 1) approximately constant magnitude (Sep. 23); 2) very rapid brightening in a period of hours (Sep. 24 – 25); 3) turnover to significantly slower brightening (Sep. 25 – 28); and 4) slow brightening, reaching peak magnitude (Sep. 30 – Oct. 9). We describe these phases in more detail below.

Between Sep. 23.56 and 23.66, the magnitude of SN 2009ip is consistent with being constant at $I = 17.39 \pm 0.05$ mag ($M_I \simeq -14.2$). However, between Sep. 23.66 and 24.45 SN 2009ip brightened by $\Delta I \simeq 0.65$ mag and continued a very rapid brightening throughout the 6 hrs of continuous imaging obtained during the night of Sep. 24. In this period, it brightened between $I = 16.7$ (Sep. 24.45) and $I = 16.2$ mag (Sep. 24.70). A linear fit to the I-band rise on Sep. 24 gives a slope of 2.30 ± 0.10 mag day^{-1}.

Between Sep. 24.70 and 25.38 the SN brightened by $\Delta I \simeq 1.0$ mag, reaching $I =$

[2]`http://www.aavso.org/apass`

[3]`http://www.sdss.org/dr7/algorithms/sdssUBVRITransform.html#Lupton2005`

15.1 mag ($M_I \simeq -16.5$). The light curve turned over to a slower brightening on Sep. 25. A linear fit to the data obtained during the night of Sep. 25 gives a slope of 0.79 ± 0.05 mag day^{-1}. The turn-over can be seen clearly in both the R and I-band photometric data obtained between Sep. 25 and Sep. 28 (see Figure 2), reaching $I = 14.1$ mag ($M_I \simeq -17.5$) by Sep. 28.47.

The latest part of the light curve between Sep. 30 and Oct. 7 shows a slow and steady brightening at a rate of 0.037 ± 0.001 mag day^{-1} (rms = 0.01 mag). However, in our most recent images obtained on Oct. 9.6 the SN faded by ~ 0.03 mag with respect to the images obtained on Oct. 7.6. The magnitude of SN 2009ip on Oct. 9.6 was $I = 13.70 \pm 0.02$ mag ($M_I \simeq -17.9$). The $R - I$ color is consistent with being constant ($R - I = -0.02 \pm 0.03$) during the period between Sep. 25 and Oct. 9.

4. Discussion

Our photometric observations, obtained during a 16-day period between Sep. 23.6 and Oct. 9.6 show that the Type IIn SN 2009ip brightened by 3.7 mag in the optical to an absolute magnitude $M_R = M_I \simeq -17.9$ (see also Margutti et al. 2012b; M12b; P12) and it has reached peak magnitude around Oct. 7 (see Figure 2). Its peak luminosity is in the observed range of Type II SNe; in fact it is more luminous than most Type IIP SNe (e.g., Li et al. 2011). The comparison to other Type IIn SNe is less straightforward since the rates are lower and the samples are incomplete. However, there are several well-studied Type IIn SNe with peak absolute magnitudes around $M \sim -18$ (e.g., Kiewe et al. 2012; Stritzinger et al. 2012; Roming et al. 2012; Mauerhan et al. 2012a).

We can estimate the total radiated energy during the period of the observations presented here. We need an estimate of the bolometric correction to convert the I-band luminosities to bolometric luminosities and we do this in two ways. First, we use the observed constant $R - I$ color, corrected for Galactic extinction, and fit a black-body to estimate the luminosity ratio $L_{\rm bol}/L_I \simeq 7$ and $T_{\rm eff} \approx 14500$ K. Second, we use the longer wavelength coverage (from near-UV to V-band) of the Swift observations presented in Margutti et al. (2012b) and fit a black-body to the extinction-corrected fluxes, obtaining $L_{\rm bol}/L_I \simeq 13$ and $T_{\rm eff} \approx 19200$ K. We integrate the I-band luminosities estimated from the extinction-corrected magnitudes. Assuming a constant bolometric correction during the 16-day observing period, we obtain a total (optical) radiated energy of $1.4 - 2.7 \times 10^{49}$ erg and luminosities of $1 - 2 \times 10^{43}$ erg s^{-1} as of Oct. 9, depending on the correction used. This is already comparable to the estimated radiated energy of the Type IIn SN 2011ht during its ~ 100 day plateau phase (Roming et al. 2012; Mauerhan et al. 2012a).

The evolution of SN 2009ip since the discovery of its latest recorded eruption on 2012 Jul. 24 (Drake et al. 2012) is quite remarkable (Figure 3; see also M12b and P12), as it is unlike any other Type IIn SNe studied to date. The absolute magnitude was approximately constant at ~ -14.5 (V to I-bands) for a period of $\sim$ 50 days after Jul. 24, and even faded to ~ -13.5 (at least between Sep. 18 and Sep. 22.5, Martin et al. 2012; Margutti et al. 2012a) before the rapid brightening that (given our observations) most likely started between Sep. 23.7 and 24.5. If we assume the maximum bolometric correction estimated above as an upper limit and a plateau phase at $M_I = -14.5$ for 50 days, we constrain the total radiated energy during this period to be $\lesssim 5 \times 10^{48}$ erg. However, we should note that the brightening could have started earlier than Jul. 24, in which case this could be a lower limit in the total radiated energy during this phase.

The spectroscopic evolution of SN 2009ip since its latest recorded eruption have also been unique. Foley et al. (2012) reported an optical spectrum obtained on Aug. 26, which showed a blue continuum with narrow (~ 700 km s^{-1}) emission lines of H and He I, similar to the spectra obtained during the 2009 eruption (Smith et al. 2009; Foley et al. 2012). Vinko et al. (2012) reported that an independent spectrum obtained on Aug. 26 also showed broad P-Cygni features with very fast velocities of $\sim 10,000$ km s^{-1}, consistent with SN shock speeds. These broad features seem to have persisted, and even strengthened, until (at least) Sep. 23 (M12b). However, the high velocity features and P-Cygni profiles had mostly gone away by Sep. 26-27, leaving behind strong, narrow ($\sim 1,000$ km s^{-1}) emission features characteristic of many Type IIn SNe spectra (M12b; Burgasser et al. 2012; Vinko et al. 2012; Gall et al. 2012; P12).

As shown in Figure 3, the transition in spectroscopic properties is coincident with the very rapid brightening observed in the optical light curves. This, most likely, marks the start of a strong interaction between the fast SN shock and a dense CSM environment likely formed from material ejected in the previous LBV outbursts, as proposed by M12b. The timing of the rapid optical brightening is also coincident with the detection of X-ray emission from SN 2009ip (Campana & Margutti 2012), which is consistent with this picture. Another possible signature of a strong ejecta-CSM interaction is the decline of $\sim$ 1 mag observed right before the spectral changes were seen and the light curve started to rise rapidly. Moriya & Maeda (2012) propose that this is an unavoidable consequence of a fast SN shock breaking out of a dense CSM.

Figure 4 shows a zoom-in view of the evolution of the optical luminosity of SN 2009ip after Sep. 23.5, which is approximately when it started to transition to a Type IIn-dominated spectrum. For comparison, we also show the optical luminosity evolution of three Type IIn SNe from the literature that have relatively well-sampled light curves before and after peak brightness. This sample includes the very luminous SN 2003ma (Rest et al. 2011) and SN 2006gy (Smith et al. 2007), and the relatively low-luminosity SN 2011ht (Roming et al. 2012; Mauerhan et al. 2012a; but see Humphreys et al. 2012).

The very early rapid optical brightening of the Type IIn SN 2009ip is consistent with $L \propto t^2$ during a short 2-day phase, although this naturally depends on the t_0 used. This is the evolution expected for an homologously expanding (optically thick) black-body photosphere at constant expansion velocity and effective temperature. The luminous Type IIn SN 2003ma and SN 2006gy show relatively similar evolution in their optical luminosity at early times before peak. In fact, Smith & McCray (2007) modeled the early rise of SN 2006gy with c model. SN 2011ht rises at a slower rate in the optical, although it was observed to rise much faster in the UV-range (Roming et al. 2012). Given the simplified assumptions that go into the $L \propto t^2$ scaling, we plan to explore more realistic models (e.g., Moriya et al. 2012) to fit the early time light curve of SN 2009ip in a future publication.

At later times, close to peak brightness, the optical luminosity and light curve shape of SN 2009ip becomes more similar to SN 2011ht than SN 2003ma or SN 2006gy. Mauerhan et al. (2012a) proposed that SN 2011ht belongs to a growing sub-class of Type IIn SNe (Type IIn-P; including also SN 2009kn, Kankare et al. 2012, and SN 1994W, Sollerman et al. 1998) with long-lasting post-peak plateaus of $\sim$ 100 days ($M \sim -18$ mag), and faint late-time decay slopes consistent with low ^{56}Ni yield production (~ 0.01 $M_\odot$). Perhaps we are seeing something similar in the case of SN 2009ip (but see P12), although there are important differences in spectroscopic properties compared to the small group of Type IIn-P SNe (e.g., SN 2009ip shows significantly hotter continuum and the narrow lines do not show P-Cygni profiles). An interesting related issue that comes out from the recent observations of SN 2009ip before the rapid brightening and fast transition to narrow-line dominated spectrum, is whether surveys might be missing a relatively low-luminosity phase (at least compared to the main peak) in which the broad SN shock velocities are revealed. Given the typical depth of transient surveys, this is certainly possible (e.g., see Fig. 17 in Kiewe et al. 2012). In fact, Smith et al. (2011b) proposed such an origin for the $\sim$ 100 day plateau at $M \sim -16$ mag observed before the main peak in the light curve of SN 1961V.

5. Conclusions

We have presented high-cadence optical photometric monitoring of the remarkable, young Type IIn supernova SN 2009ip using data obtained between 2012 Sep. 23 and Oct. 9 with 0.3-0.4 meter aperture telescopes from the Coral Towers Observatory (Cairns, Australia). Using difference imaging analysis, we obtain precise R and I-band light curves and are able to resolve well-defined brightening phases. In particular, we see a very rapid brightening early on (0.5 mag in 6 hr) that quickly turns over after a couple of days. The SN brightened between absolute magnitude $M_I = -14.2$ and $M_I = -17.9$ in 16 days. The changes that we observe in the light curves are correlated with the reported spectroscopic changes and the X-ray detection, and, most likely, mark the start of a strong interaction between the fast SN ejecta and the dense CSM formed from material that was ejected in the pre-supernova LBV eruptions observed since 2009. Our study highlights the importance of organized, high-cadence observations by amateur astronomers with small-aperture telescopes and the impact they can have in transients and SNe research, in this case with direct important connections to massive stellar evolution.

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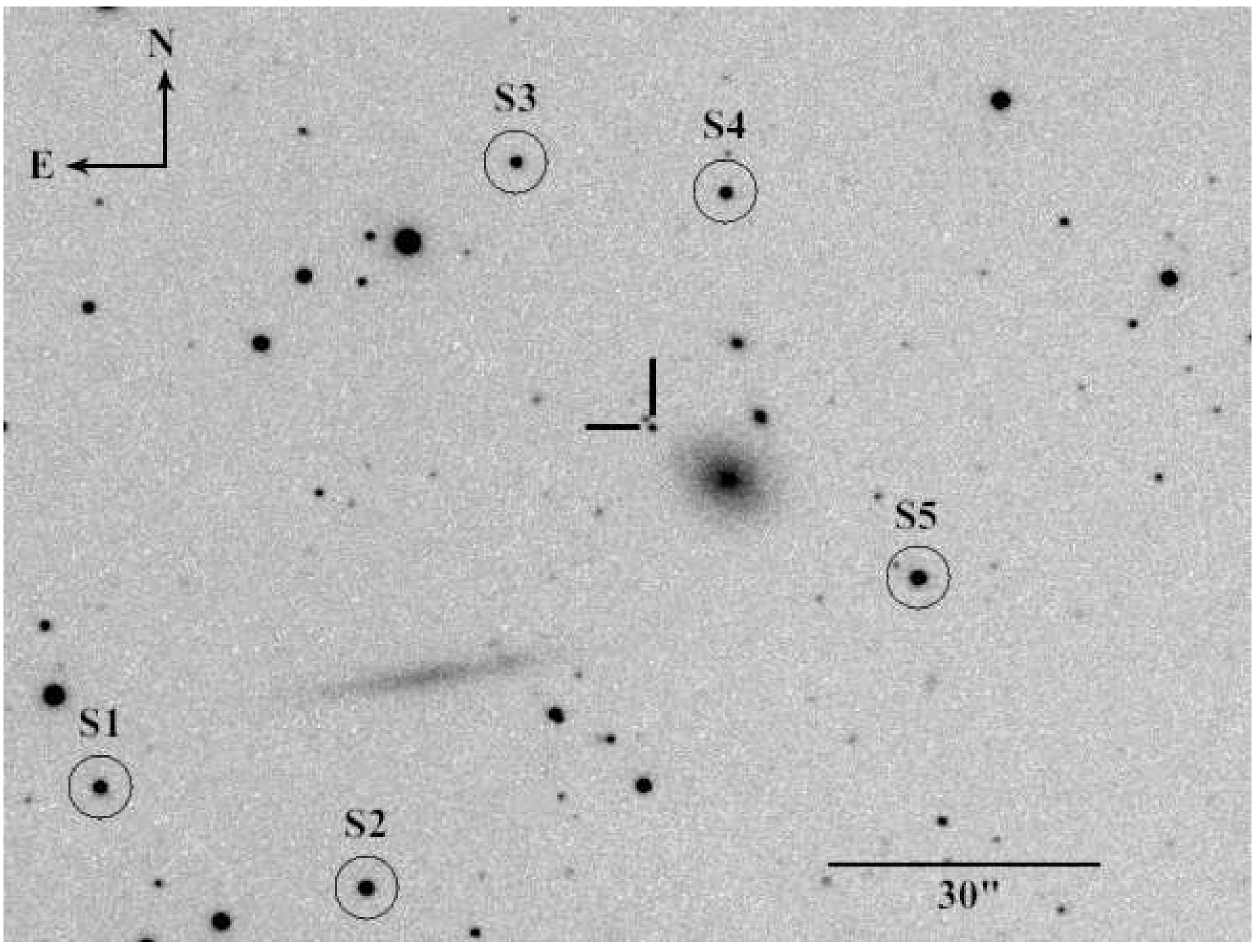

Fig. 1.— Finding chart of SN 2009ip. This image was obtained with the IR filter on 2012 Sep. 24. The circles mark the local standard stars used to estimate the photometric zeropoints and the cross-hairs show the position of SN 2009ip.

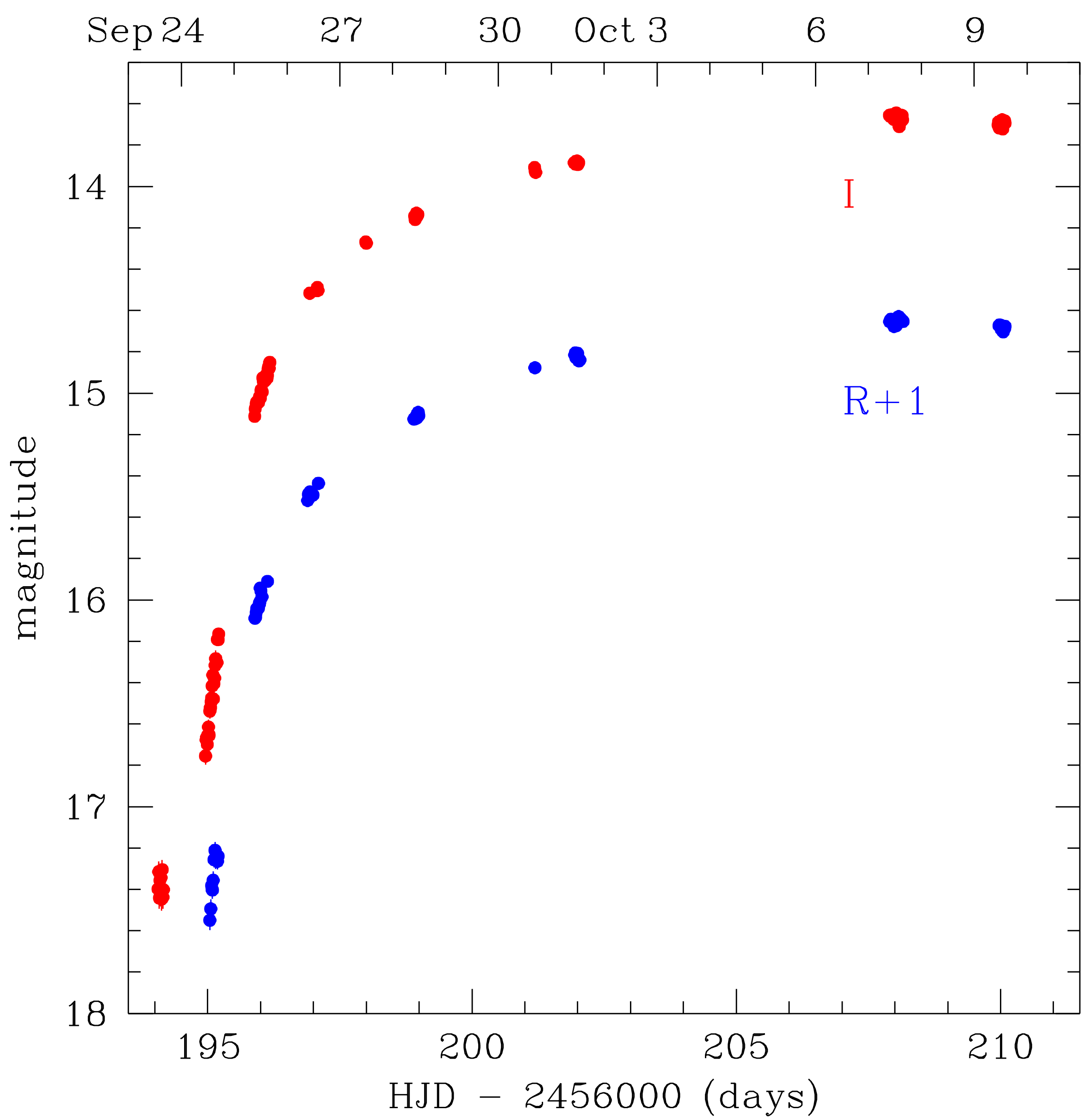

Fig. 2.— Light curves of SN 2009ip in the R and IR (> 700 nm) bands, calibrated to standard R and I magnitudes, respectively. The data were obtained by J. Brimacombe between 2012 Sep. 23.6 and Oct. 9.6 from the Coral Towers Observatory (Cairns, Australia).

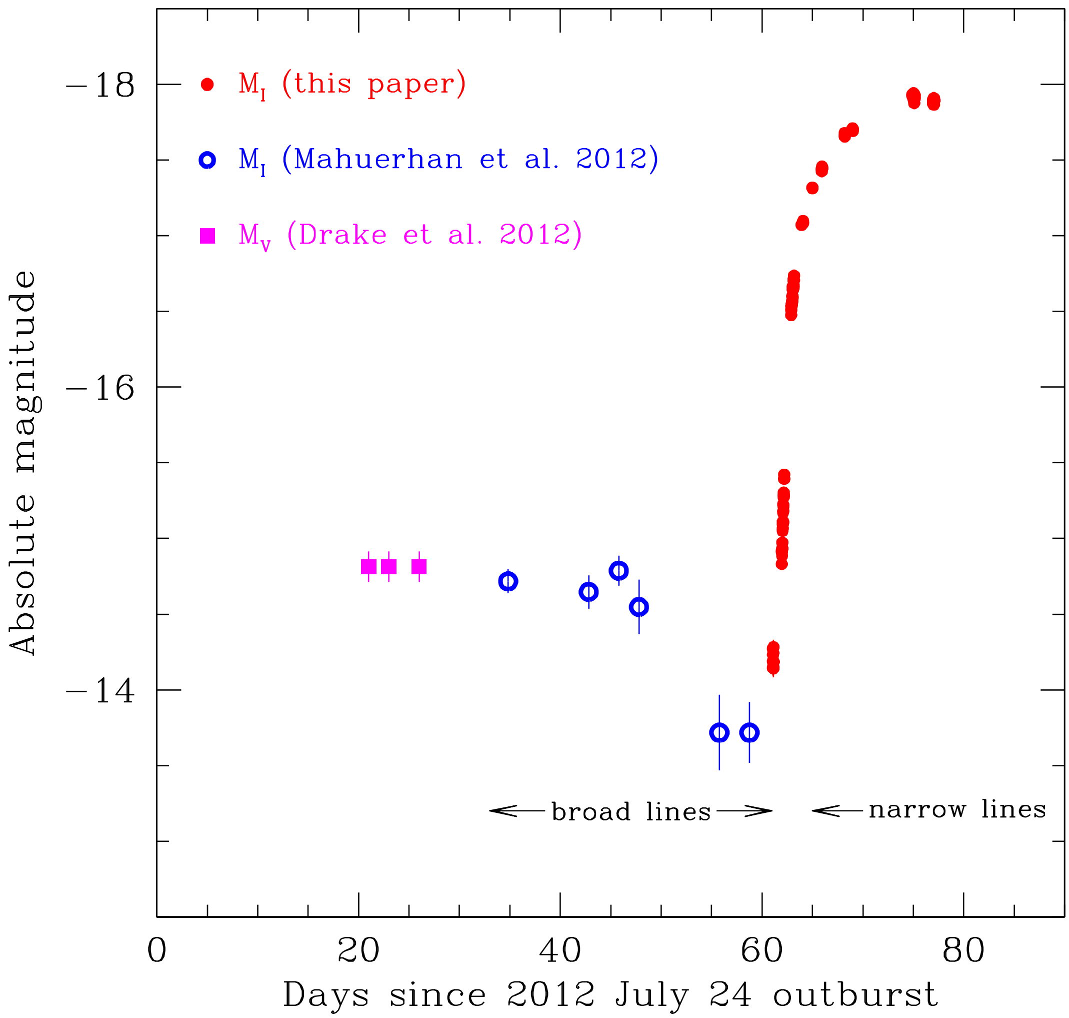

Fig. 3.— Absolute magnitude light curve of SN 2009ip since its latest eruption was reported on 2012 July 24 by Drake et al. (2012). The filled circles are the I-band photometry presented in this paper; the open circles are I-band photometry reported in Mauerhan et al. (2012b); and the filled squares are V-band photometry reported in Drake et al. (2012). The spectrum of SN 2009ip showed broad H and He I emission lines with P-Cygni profiles ($v \simeq 10,000$ km s^{-1}), characteristic of SN shock speeds, starting on (or before) Aug. 26 (Vinko et al. 2012; but see Foley et al. 2012) until, at least, Sep. 23 (Mauerhan et al. 2012). However, by Sep. 26 − 27 the spectrum had changed substantially (Mahuerhan et al. 2012b; Burgasser et al. 2012; Vinko et al. 2012) and the emission lines became strong and narrow ($v \sim 1,000$ km s^{-1}), resembling the spectra of Type IIn SNe. These phases in the spectral evolution are shown schematically with arrows. The change to a narrow-line dominated spectrum is coincident with the very rapid brightening observed in the light curve.

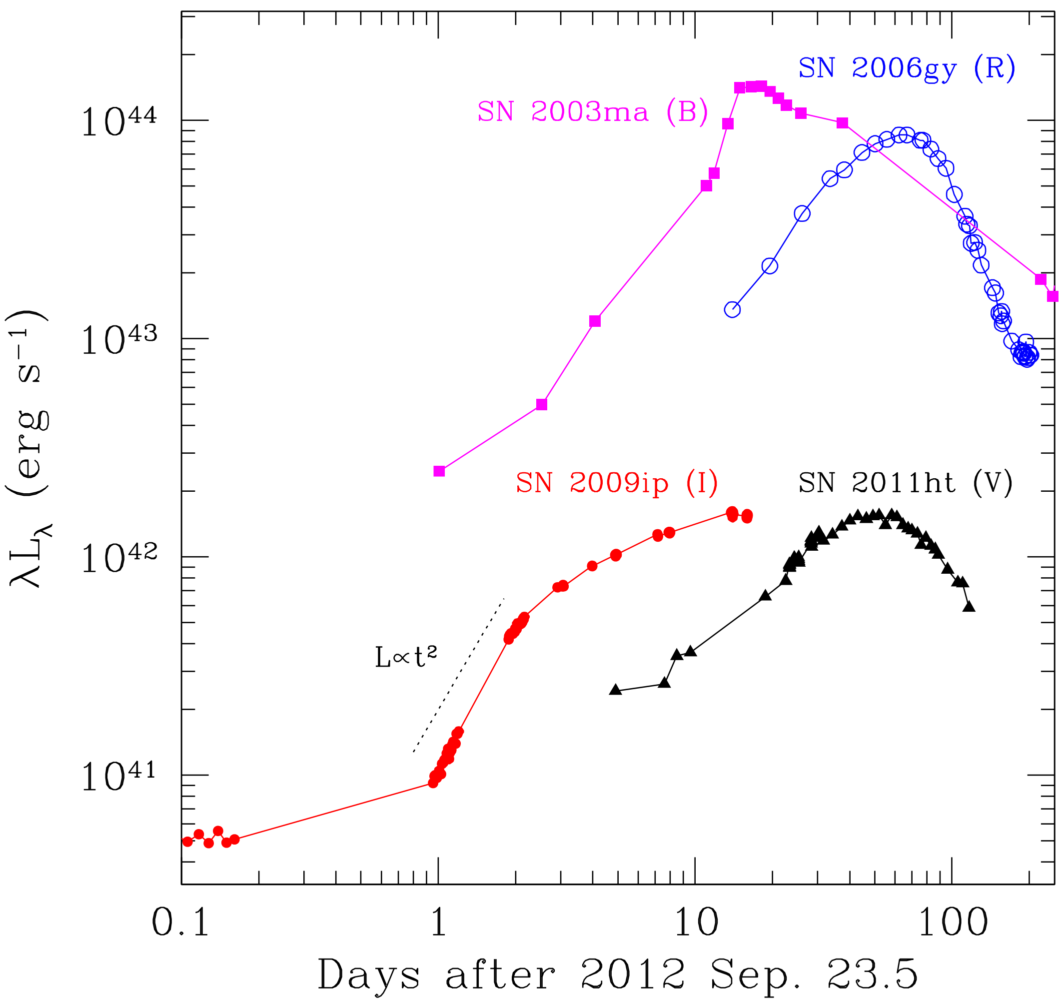

Fig. 4.— Early rise in optical luminosity of the Type IIn SN 2009ip (filled circles) since 2012 Sep. 23.5. We also show for comparison the luminosity evolution in the rest-frame optical of other Type IIn SNe (filters used indicated in parenthesis) with good light curve coverage before and after peak brightness. These include: SN 2003ma (filled squares; Rest et al. 2011), SN 2006gy (open circles; Smith et al. 2007), and SN 2011ht (filled squares; Roming et al. 2012). We have used the distances, extinctions, and K-corrections provided in each paper to derive the luminosities. The time in these cases is estimated with respect to an approximate explosion date (SN 2003ma and SN 2006gy) or with respect to the discovery date (SN 2011ht). The dotted line shows the luminosity scaling $L \propto t^2$.

Table 1. Light curve of SN 2009ip

UT Date	HJD - 2456000	mag	σ	Filter
Sep 24.536400	195.040909	16.549	0.047	R
Sep 24.552130	195.056641	16.494	0.045	R
Sep 24.567801	195.072327	16.382	0.040	R
Sep 24.583472	195.087997	16.403	0.043	R
Sep 24.599144	195.103668	16.356	0.044	R
Sep 24.614826	195.119370	16.256	0.039	R
Sep 24.633634	195.138153	16.211	0.040	R
Sep 24.644965	195.149475	16.259	0.043	R
Sep 24.656285	195.160797	16.256	0.040	R
Sep 24.667593	195.172134	16.250	0.038	R
...	...	...	...	R

Note. — The full table will be available as a machine readable table.